An optimized practical solution for construction of cross passage in soft ground mechanized tunnelling in urban area

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Abstract

The construction of underground cross passages is one of the main concerns in soft ground mechanized tunnelling in urban area. They are constructed to connect running tunnels at prescribed intervals along the alignment to meet safety requirements during service stage. In most cases, the cross-passages are to be constructed in poor ground and under piezometric level as well as in urban congested environment. Therefore, the design and construction of cross passage is regarded as the very challenging task in tunnelling. The main challenging operations in constructing cross passes, apart from ground improvement, are the creation of stable and safe work condition at the moment of lining cutting and the formation of permanent concrete collar at intersection before commencement of the cross passage excavation. This paper deals with a practical solution in order to optimize the design and construction of cross passage. In more details, the proposed solution offers the installation of temporary steel frames “half-moon solution” in running tunnels, to ensure the stability of intersection area between the cross passage and the running tunnel and to provide a safe work condition at the moment of cutting of the segmental lining and opening of the cross passage. The construction of safely permanent collar structure is also focused in this paper. The proposed method provides the structural analysis implementing the application of different ground load combinations and staged excavation by Finite Element Analysis “STRAUS7” so as to effectively model the construction stages and lining-ground interaction. The recommended design and structural analysis as well as the optimized design solution which are presented in this paper have been adopted through realistic results and conclusions of many real case histories implemented in GEODATA Engineering over many years of experiences.

Keywords

Cross passage, soft ground tunnelling, segmental lining, numerical model, STRAUS7, segment cutting

Design approach

The construction of cross passage, followed in this study, is generally divided into (1) ground treatment, (2) assembly of temporary steel frame, (3) segment cutting, (4) opening the cross-passage space, (5) first round of cross passage excavation, (6) in-situ casting permanent concrete collar, (7) disassembling steel frame and (8) successive rounds of cross-passage excavation. The aforementioned steps are contemporarily utilized from both TBM segmental lined tunnels. As observed, before commencement of excavation of cross passage, three main steps should be taken into consideration: (a) ground treatment, (b) setting up the temporary steel frame, and (c) cast in-situ permanent concrete collar at intersection.

Applied ground treatment

Seeing that most of the cross passage are constructed in soil like materials with poor strength parameters and very short stand-up time, mixed-face layers with different permeability characteristics, under piezometric levels, so the first step in construction is to primarily create an impervious layer around intersection area and to enhance the shear strength parameters of surrounding soft ground. The methods and criteria for the application of ground treatment are given elsewhere in the other publications of the authors.

Setting up temporary steel frame

During construction, before demolition of the segmental rings at intersection area a temporary steel frame should be set up at the junction of the cross passage with segmental lined tunnels. This temporary supporting steel frame provides the required stability of the junction zone on the re-distribution of the ground stress at the junction and safety on the work. This temporary steel structure shall be of proper rigidity and stiff in order to minimize ground deformation. The opening and the excavation of cross passage shall start once the steel frame and concrete collar are set up, respectively.

Cast in-situ permanent concrete collar

In order to establishment of a permanent structure at cross passage junction to provide safe work condition and to improve the stability in terms of moderating deduced stresses in the segmental lining and to decrease the stress concentration at junction, the permanent collar structure should be built. This will be part of the final lining of the intersection. Fig. 1 shows the involving structures in proposed design solution, including temporary steel frame and cast in-situ permanent concrete collar.

Design parameters used in this study

Geotechnical setting

A large set of ground geotechnical parameters with quite enough variation have been considered to handle the ground uncertainties and variability in such a shallow soft ground tunnelling condition. The overburden [H] varies between D and 4D, in which D is the tunnel diameter. Considering such variation in geotechnical parameters makes it possible to let the results of the analysis be more reliable, resulting optimized design solution to be used in any similar geotechnical context. The cross passage is assumed to be always under piezometric level such that for the long-term design it will reach to ground surface. Depending on the type of ground in soft ground tunnelling, Table 1 presents the design geotechnical parameters used in proposal design solution.

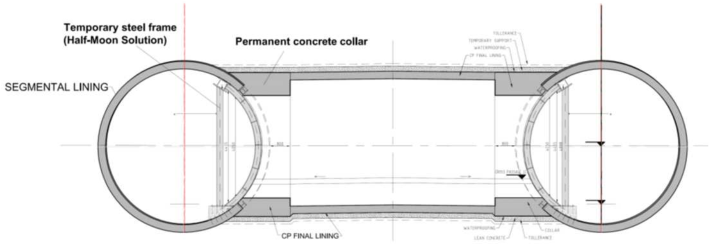


Figure 1. Longitudinal cross section of a typical cross passage constructed by proposed design solution

Table 1. Geotechnical design parameters

Ground type	Saturated unit weight [γ_{sat}]	Ground modulus [E']	Effective cohesion [c']	Effective friction angle [ϕ']	Undrained shear strength [Su]	Over-consolidation ratio [OCR]	Permeability, kh	Permeability, kv
	kN/m^3	MPa	kPa	°	kPa	-	[m/day]	[m/day]
Sandy governing layers	18-21	40-80	0	30-34	-	1.5-4.0	1.0-15.0	0.3-5.0
Clayey layers	16-20	24<	0.1-5	30	60-100	1.0-2.0	0.0001-0.001	0.0003-0.0001
Highly fractured rock and silty sand layers	20-21	100-200	5-200	30-38	-	4.0-6.0	0.001-2.0	0.0003-0.5

Characteristics of segmental tunnel lining

For this study, a medium size tunnel commonly designed for metro projects is considered. The internal diameter of tunnel is 6.0m and the tunnel lining is assumed to have a thickness of 30cm and length of 1.6m. The applied class of the concrete is C60/75, f_{ck}=60MPa, in accordance with Eurocode (2005). Each segmental ring consists of three standard segments, two counter key segments and one key segment. The lining has flat concrete-to-concrete circumferential joints. The radial joints are temporarily bolted with straight bolts in pockets whereas the circumferential joints are linked with # 16 plastic dowels (3 dowels for each segment and one for key-stone). The primary reinforcing element used in concrete segments at the cross passage intersection area shall be conventional steel rebar, often accompanied with reasonable quantity of steel fibres.

Table 2. Characteristics of engineering materials

Concrete	f_{ck}=40MPa	E_c=33000MPa $E_{c,\ long\text{-}term}$=16500MPa	ρ_c=2400kg/m^3
Steel reinforcement	f_{sy}=500MPa	f_{sd}=400MPa	
Steel frame	Grade =350 UC	f_{sfy}=350MPa	E_{sf}=200GPa
Steel bolts	M20 & M24	$f_{uk,\ M24}$=830MPa $f_{uk,\ M20}$=400MPa	E_b=200GPa

f_{ck} =Uniaxial compressive strength of the concrete in 28dyas (cylindrical)

E_c, $E_{clong\text{-}term}$ = Elastic modulus of concrete, long term elastic modulus

f_{sy} = Characteristics yield strength of the steel reinforcement

f_{sy} = Design yield strength of the steel reinforcement

f_{sfy} = Characteristics yield strength of the steel frame

f_{uk} = Characteristics tensile strength of bolt

E_{sf} = Elastic modulus of steel frame

E_b= Elastic modulus of bolt

ρ_c = concrete density

Characteristics of the engineering materials used in steel frame and concrete collar

The characteristics of the engineering materials used in different component of the cross passage opening structures; namely, temporary steel frame and the cast-in situ concrete collar are well defined in Table 2.

Method of numerical calculations

The global 3D structural model, using plate-spring elements, is used to assess membrane forces on both temporary steel frame and permanently cast in-situ concrete collar (Fig.2). Particularly, as regards the segmental lined tunnels, the 2D Finite Element (plates) is modelled. As far as temporary steel frame is concerned, the 3D Finite Element (bricks) pretends both upper and lower steel horizontal beams while the 1D beam elements allow for the vertical and curved steel columns. Furthermore, the elastic bedded-springs (only compression) takes into account the interaction between soil and segmental lining. Regarding cast in-situ concrete collar, the 3D elements (bricks) is used.

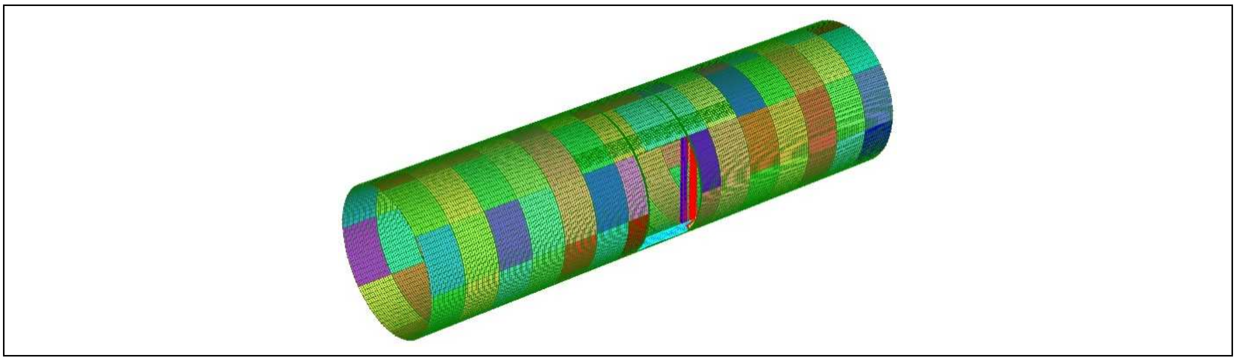


Figure 2. 3D Model of the problem-geometry of STRAUS7 Model

Regarding the boundary conditions of the 3D model, 15 segmental rings of running tunnel are considered such that the length of the numerical model to be 24m to avoid any numerical disruption at borders. The cross passage opening cut dimension is 2.6m×5.2m (width-height). The polar coordinate system is acknowledged to adopt for the model such that the segmental lined tunnel is constrained in its longitudinal direction.The stiffness of the ground reaction is based on a modulus of subgrade reaction (K), which can be calculated by several different methods, of which the so-called Galerkin method is suggested. (Bowles, 1982).

$$k_n = \frac{E}{R_{eq}(1+\nu)}$$

where E is ground deformation modulus, v is the ground Poisson coefficient, and R_{eq} is equivalent radius of the tunnel. The development of global 3D model of the problem complies with the following distinct steps:

1. Determination of load acting on cross passage intersection

Due to heterogeneity of the ground soil layers and stress ratio, instead of empirical approach, the ground load is calculated by means of 2D PLAXIS, a Finite Element Analysis which is quick and quite user-friendly. In this way, it is possible to examine the different load combinations to increase the reliability of the solution. Hence, the axial force on the TBM segmental lined tunnel is easily calculated. Such an axial force can be inverted into the acting ground pressure around the tunnel circumference through Mariotte shell theory.

$$q = \frac{2N_K}{D_{eq}}, \; N_k = \sigma_k \times t_c$$

where N_k [kN/m] is the axial force per meter of the tunnel obtained by 2D PLAXIS, σ_k [kN/m^2] is the circumferential stress, D_{eq} [m] is the equivalent diameter of the tunnel, t_c [m] is the thickness of the segmental lining. The resulting radial ground pressure (q) [kN/m^2] is then applied in a radial form in STRAUS7 model in such a way that it varies linearly from one to another node of the model. Through this precise application of the pressure in the calculation model it is possible to apply a variable pressure along the entire segmental ring layout.

As far as the structure of concrete collar is concerned, seeing that it is a permanent structure and on the account of the soft ground shallow depth condition, Terzaghi's formulation is used to determine the acting load. It is due to take into account the gravity weight of the ground acing on the structure and to dimension of the rigid lining with adequate quantity of steel reinforcement.

2. Modelling of segmental lined tunnel

The TBM tunnel lining has been simulated by means of Plate Elements being 30cm thick, elastic modulus of 36500MPa, density of 2400kg/m^3. The interaction between tunnel lining and ground has been taken into account through elastic springs with non-linear behaviour (only compression). As far as the connecting system between the successive segmental rings is concerned, the connection has been simulated by means of dowels elements modelled by elastic-plastic regime to model properly the connection behaviour. The behaviour of these elements is governed by both actual curves of shear force- displacement and pull-out force- displacements which are derived through laboratory tests provided by supplier. The maximum shear force reach to 140kN at displacement of 10mm while the maximum pull-out force reaches as much as 110kN corresponding to axial displacement of 8mm. such rigidity should be given in STRAUS7model. The skin friction between rings is considered with point contact elements considering μ= 0.15 and μ=0.3.

3. Modelling of the temporary steel frame

The temporary steel frame structure is composed of six straight columns, six curvature columns, an upper beam is composed of two coupled profiles and basement beam is composed of two coupled profiles (Fig.3).

The upper beam, composed of two coupled profiles (profile type HE), has been modelled through 3D elements (Bricks model) that characterized as E=2.0×108kPa and γ=7850kg/m^3. Similarly,the curvature and the straight columns were modelled through Mono-dimensional (1D) elements, beam with the same characteristics. The basement beam, composed of two coupled profiles (profile type HE), has been modelled through 3D elements (Bricks model).

The interaction between the segment and the upper- lower steel beams is modelled in STRAUS7 through "Connection" elements, evenly distributed, able to transmit only axial and shear forces to the temporary steel frame. The entire shear force is then used for dimensioning such connections (bolts with epoxy resins). The connection between the concrete segment and upper and lower steel beams are provided by means of anchor bolts of M24. The entire shear force is then used for dimensioning such connections (bolts and welding). In this complex junction, the connection among the upper steel beam, straight and curvature columns are also provided by means of bolts, plates, and welding (Fig. 3).

4. Modelling of the permanent cast in-situ concrete collar

In the same way, the 3D model of the permanent cast in-situ concrete (Fig.4) collar is implemented. The concrete collar has been simulated by means of 3D Brick Elements whose characteristics given in Table.2. The interaction between reinforced concrete collar and ground has been taken into account through elastic springs with non-linear behaviour (compression action). The interaction between TBM tunnel segmental linings and concrete collar has been simulated with rigid connection elements capable of transmitting only normal stress (without any shear component) and avoiding any interconnection.

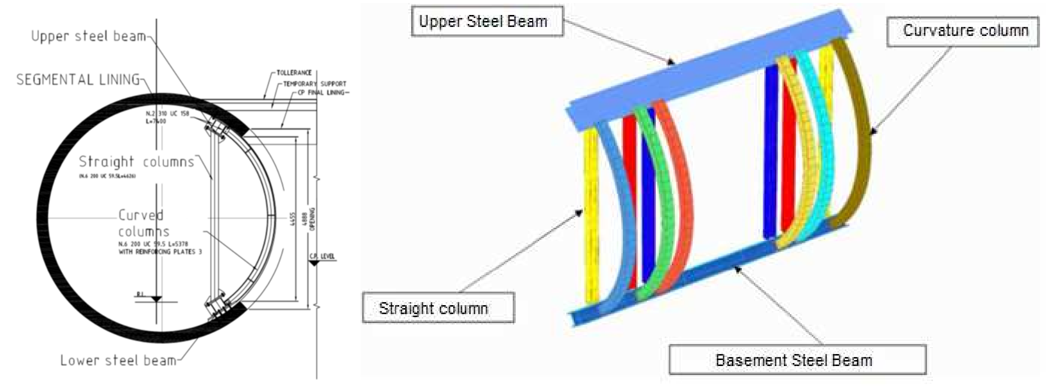


Figure 3. Temporary Steel Frame: Structural steelwork and 3D STRAUS7 model

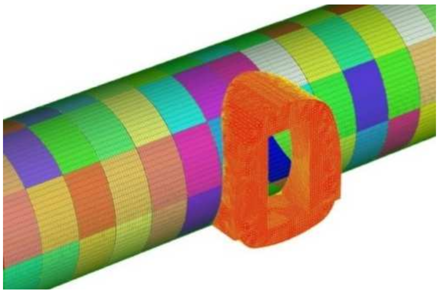


Figure 4. Permanent cast in-situ reinforced concrete collar at cross passage opening area - 3D Model

5. Design loads and load combinations

The next step in developing 3D STRAUS7 model is the definition of the loads and different combinations. With reference to accepted international guidelines and recommendations, the design load should be considered, of which the ground and water load constitute the major loading and the other secondary loads set up the additional load combinations. The loads should be combined with each other, generating appropriate load combinations. The load combinations are assigned to the construction stage where they occur. The mentioned loads are interchanged among them depending on model requirements so as to examine the most suitable load combinations in desired stage of the model.

6. Modelling of staged-excavation and construction

A non-linear multi-staged analysis was carried out through STRAUS7 to define the maximum stresses acting (membrane forces) on the structural elements. Six separate stages have been created to analyse the behaviour of the involving structures during construction and long term service life.

The 1st stage concerns the geostatic undisturbed condition of the segmental line tunnel and cross passage opening area before any demolish and opening operation. In this stage the loads due to the ground and water pressure are applied. The 2nd stage deals with the installation of the temporary steel frame structure (half-moon solution) at cross passage opening area where the ground stress concentration will take place due to re-distribution of undisturbed filed stress. In this stage, the same loads of the previous stage are applied. In 3rd stage, the two adjacent segmental rings are demolished resulting in re-distribution of stress around the cross passage intersection area. Even though the applied load is not changed compared with stage #2, the deduced axial force and flexural moment were expected to be increased in segmental lined close to intersection area, which it is sought in this study.

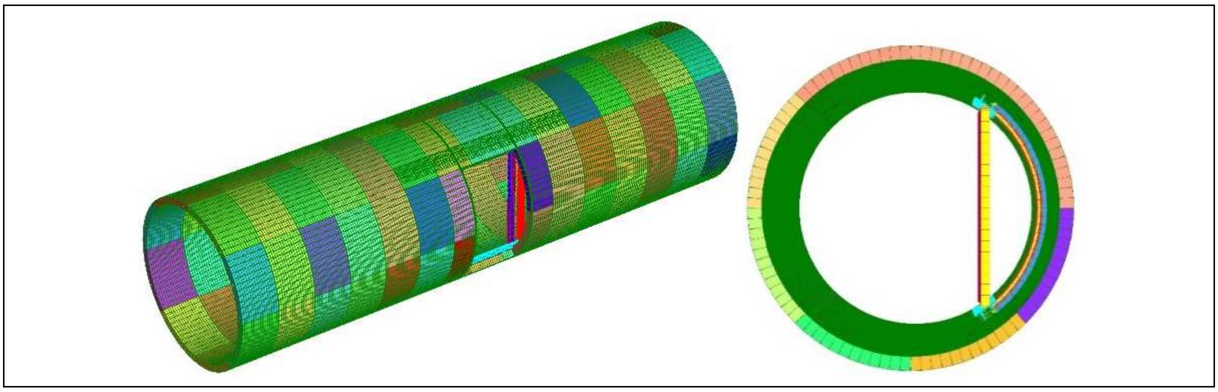


Figure 5. Stage 3 of multi-staged modelling: TBM tunnel segmental rings demolished in presence of steel frame structure and influenced segmental rings withstands higher stresses

As the integrated part of the cross passage at intersection area, the permanently reinforced concrete collar to be constructed cast in-situ in stage 4th so as to withstand and moderate the deduced axial force and flexural moment at intersection area and to ensure the stability of this critical area. This cast in-situ concreted collar is regarded as a permanent component of the cross passage and guaranty the durability issues as well (Fig. 6). In 5th stage, the temporary steel frame structure has been removed. In this stage, it is important to verify that there were no stresses in the TBM tunnel segments greater than those induced in 3rd stage. If no, it was necessary to increase the dimensions of the concrete collar to moderate the stress re-distribution. In this stage, all load cases and load combinations should have been examined on the intersection structure so as to satisfy the required structural verifications in ultimate state (Fig.6).

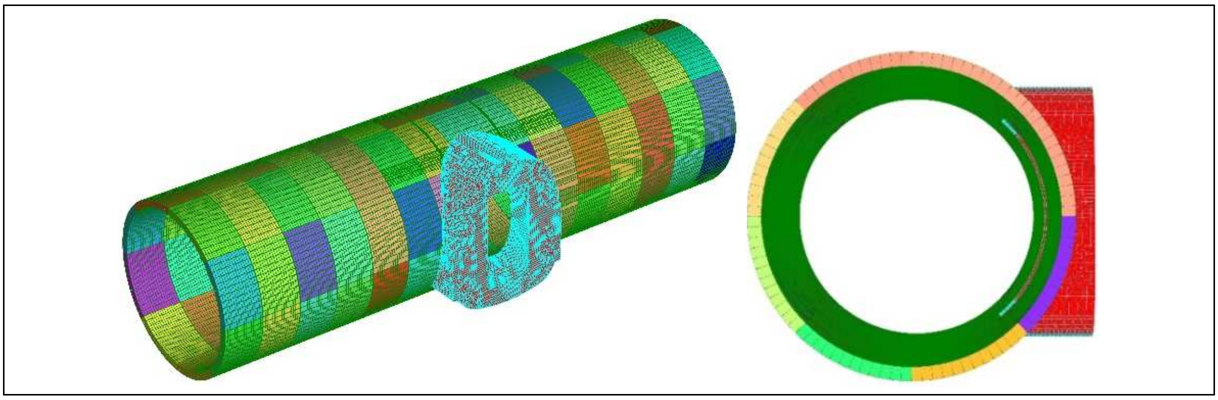


Figure 6. Stages 4 and 5 of multi-staged modelling: Permanent reinforced concrete collar in-situ casting prior and after dismounting the steel frame

Analysis of the numerical results

Having been carried out the multi-staged modelling through STRAUS7 model, the main objective is to determine the membrane forces (stresses) deduced in the involving structure, successively to be used in structural verification in limit state. The proposed solution should offer a practical result in terms of ensuring stability of the segmental tunnel, controlling and ceasing ground deformation, ensuring safe work condition during demolition of segmental rings and cross passage opening cut by also moderating deduced ground stresses by construction of concrete collar. Consequently, in terms of stability in limit state condition, the structural verification of segmental rings, steel frame, and the concrete collar should be satisfied.

Analysis of the temporary steel frame

The temporary steel frame shall be overstressed while cutting the segmental ring to open the cross passage as well described in Table 3 which related to the stage 3 of modelling. As observed, the basement steel profile withstands higher stresses compared to the other elements, of which the structural verification in ultimate limit state should, therefore, be satisfied.

Table 3. Acting membrane forces on temporary steel frame upon opening cut

Upper Steel Beam

	Section A					Section B				
	N [kN]	M_1 [kNm]	M_2 [kNm]	V_1 [kN]	V_2 [kN]	N [kN]	M_1 [kNm]	M_2 [kNm]	V_1 [kN]	V_2 [kN]
MAX	-384.70	-242.50	-194.00	-6.00	13.50	-158.00	-97.30	-66.40	397.30	437.20
MIN	-109.60	-70.00	-58.00	-2.40	4.00	-45.60	-27.50	-20.90	114.90	126.00

Basement Steel Beam

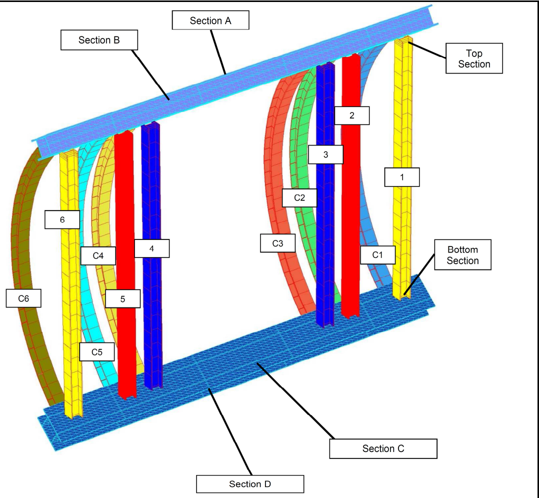
	Section C					Section D				
	N [kN]	M_1 [kNm]	M_2 [kNm]	V_1 [kN]	V_2 [kN]	N [kN]	M_1 [kNm]	M_2 [kNm]	V_1 [kN]	V_2 [kN]
MAX	-648.81	-226.35	172.21	-31.96	-1.04	-538.28	-98.39	61.15	-439.15	428.87
MIN	-182.91	-154.45	223.47	24.99	-10.49	-111.57	-115.25	-134.56	-336.05	193.54

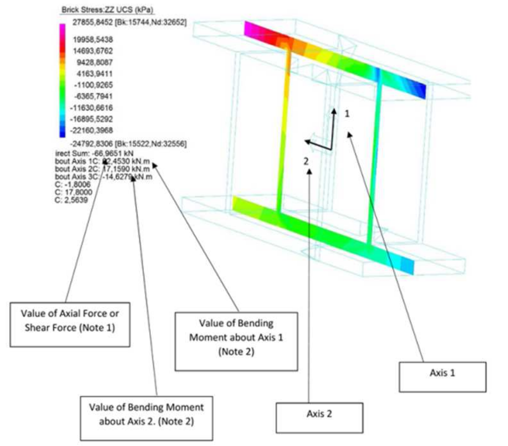
Straigth Steel Column

	Top Section							Bottom Section					
	1	2	3	4	5	6		1	2	3	4	5	6
MAX	265.05	456.24	697.80	709.62	461.06	294.01	N [kN]	267.67	458.86	700.42	712.24	463.68	296.63
	0.00	0.00	0.00	0.00	0.00	0.00	V [kN]	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	M [kNm]	0.00	0.00	0.00	0.00	0.00	0.00
MIN	3.83	74.45	150.17	155.59	77.57	5.06	N [kN]	2.37	77.06	152.76	158.20	80.19	7.68
	0.00	0.00	0.00	0.00	0.00	0.00	V [kN]	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00	M [kNm]	0.00	0.00	0.00	0.00	0.00	0.00

Curved Steel Column

	Top Section							Bottom Section					
	C1	C2	C3	C4	C5	C6		C1	C2	C3	C4	C5	C6
MAX	158.61	45.32	195.04	206.21	69.74	175.40	N [kN]	160.65	48.17	197.94	209.12	72.54	177.49
	-11.17	-4.71	-15.33	-16.26	-6.75	-12.70	V [kN]	-93.51	13.70	35.97	38.34	10.15	-84.83
	0.00	0.00	0.00	0.00	0.00	0.00	M [kNm]	0.00	0.00	0.00	0.00	0.00	0.00
MIN	63.45	18.76	66.83	70.74	26.76	67.40	N [kN]	66.06	21.59	69.67	73.58	29.59	70.01
	-3.38	-0.95	-4.02	-4.38	-1.37	-3.79	V [kN]	-30.98	7.39	14.06	14.83	8.20	-28.05
	0.00	0.00	0.00	0.00	0.00	0.00	M [kNm]	0.00	0.00	0.00	0.00	0.00	0.00





The structural verification for basement steel profile should satisfy the axial force-bi-axial flexural moment as:

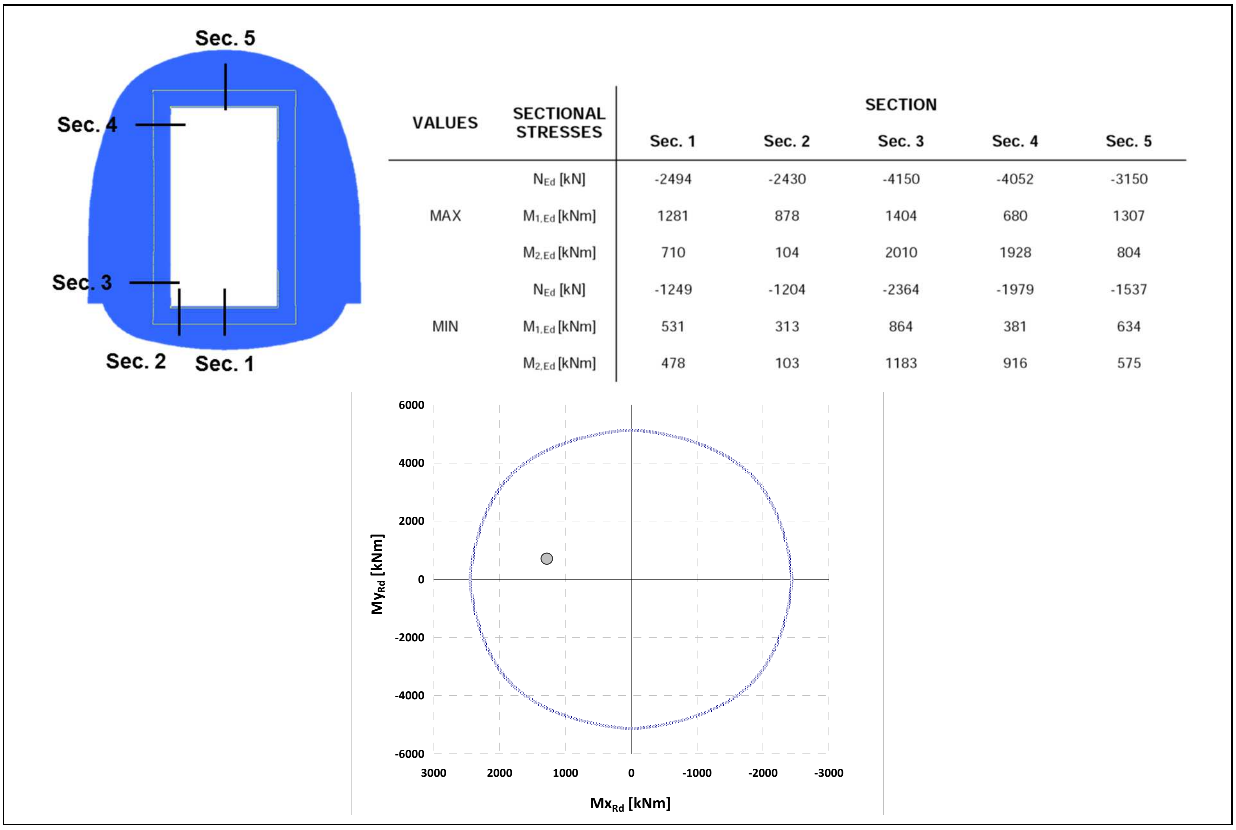
$$\frac{N^*}{\phi Ns}+\frac{M_2^*}{\phi Msx}+\frac{M_1^*}{\phi Msy}\leq 1.0$$

In which, N (unfactored, referred to two beams) = 648.8 kN, N* (factored, referred to one beam) = 437.9 kN, M_1 (unfactored, referred to two beams) = 226.3 kNm, M_1* (factored, referred to one beam) = 152.8 kNm, M_2 (unfactored, referred to two beams) = 172.2kNm, M_2* (factored, referred to one beam) = 116.24 kNm. Φ is strength reduction factor (here is considered 0.9). Hence:

$$\frac{437.9}{5065.2}+\frac{116.2}{675.4}+\frac{152.8}{305.1}=0.76\leq 1.0$$

Analysis of the permanent cast in-situ concrete collar

Similarly, the cast in-situ concrete collar, its analysis section is presented in Fig.7, will be expected to be overstressed while dismounting the temporary steel frame as per stage 5 of the sequential modelling. The deduced membrane forces are presented in Fig.7. As can be inferred, the section 1 is more overstressed compared to the others whose structural verification in is satisfied (Fig.7).



VALUES	SECTIONAL STRESSES	SECTION Sec. 1	Sec. 2	Sec. 3	Sec. 4	Sec. 5
MAX	N_{Ed} [kN]	-2494	-2430	-4150	-4052	-3150
	$M_{1,Ed}$ [kNm]	1281	878	1404	680	1307
	$M_{2,Ed}$ [kNm]	710	104	2010	1928	804
MIN	N_{Ed} [kN]	-1249	-1204	-2364	-1979	-1537
	$M_{1,Ed}$ [kNm]	531	313	864	381	634
	$M_{2,Ed}$ [kNm]	478	103	1183	916	575

Figure 7. Details of the numerical analysis of the concrete collar. Upper left: nomination of involving sections, upper right: deduced membrane forces, Lower: ULS verification of the section 1 of concrete collar (applied conventional steel reinforcement:2×9ϕ20+2×6ϕ20 for two concerned axis subjected to flexural moment)

Conclusions

A practical solution in order to optimize the design and construction of cross passage has been presented in this paper. The proposed solution offers a safe work condition at the moment of cutting of the segmental lining and opening of the cross passage. The usage of non-linear 3D structural Finite Element Analysis through STRAUS7 makes it possible to examine the application of different ground load combinations and sequential staged-excavation so as to effectively model the construction stages and lining-ground interaction. The re-distribution of the ground stresses up on segment demolition is, in turn, modelled by STRAUS7. Briefly, the staged-construction brings about the following significant conclusions:

- The most critical stage for the structure occurs during the cutting / demolition of the TBM segmental rings due to re-distribution of the stress and consequent stress concentration at intersection area. It is imperative to investigate the deduced stresses (axial force and flexural moment in bi-axial direction due to 3d nature of the model) in segmental lining neighbouring to the intersection after realization of permanent concrete collar and removal of the temporary steel frame. The geometry of the collar should be designed such that the deduced stresses in segmental remains admissible at ultimate state during the removal stage of the temporary steel structure;
- The increase of non-symmetrical load, due to the heterogeneous ground load at intersection, obliges to apply the conventional steel reinforcement types of TBM tunnel segments.
- The use of an extremely rigid temporary steel frame limits the deformation of the segmental lining and the tangential stresses in the dowels (connecting system between segmental rings), but increases the stresses in the segmental lining. The optimal solution may be adopting a temporary steel frame that provides similar rigidity of the permanent concrete collar.
- It is recommended to analyse a further stage to take into account the creep deformation effects of concrete at time $t \rightarrow \infty$ for a constant compressive stress σ_c applied at the concrete age t_0.
- The last but the most important finding to be obligatorily followed during construction stage is that the opening cut should be centred with respect to the axis of the centre ring, if not, a non-symmetrical loading impacts negatively the adjacent rings and the deduced flexural moments will be out of control.
- The proposed solution has examined also the collision effect, an unavoidable risk in underground due to human or machinery mistake. The finding of analysis revealed that the re-distribution of the stresses in absences of one damaged columns does not any impact on the global stability of the steel frame and the safety of the working area is kept guaranteed.

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